REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Sept 1980	Final Sept 30, 1979– Sept 20, 1980

4. TITLE AND SUBTITLE
BASIC INSTABILITY MECHANISMS IN CHEMICALLY REACTING
SUBSONIC AND SUPERSONIC FLOWS

5. FUNDING NUMBERS

61102F
2308/A2

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8. PERFORMING ORGANIZATION REPORT NUMBER

AFOSR.TR. 89-1632

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR
BLDG 410
BAFB DC 20332-6448

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AFOSR-78-3662

DTIC
ELECTE
DEC 06 1989
S B D

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
The stability of one-dimensional piston-supported detonations has been examined
both numerically and analytically. Numerical calculations were conducted for a
one-step, first-order, irreversible reaction obeying an Arrhenius rate expression.
An approximate linearized stability theory was also developed for the case of high
activation-energy reactions and the mechanism of instability identified. The
Analysis demonstrates that the interaction between the irreversible temperature
fluctuations and the reaction zone induces an oscillatory energy- source field,
which then leads to shock perturbations and thereby the temperature fluctuations.
The frequencies of all the unstable and stable modes of this system can be
predicted. They agree remarkably well with the findings of the numerical calculations
and the observations in blunt-body flow experiments. The problem of direct initiation
of gaseous detonations was also examined theoretically, to determine the correlation
between the critical energy and power for successful initiation, and to predict
their respoective threshold values. The results were found to agree well with the
experimental observations of cylindrical detonations in oxy-acetylene mixtures.
One paper is in press and another two papers have been prepared for journal publication.

14. SUBJECT TERMS

15. NUMBER OF PAGES
16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified		

89 12 05 111

ANNUAL TECHNICAL REPORT ON RESEARCH

SUPPORTED BY GRANT AFOSR-78-3662

(September 30, 1979-September 29, 1980)

Basic Instability Mechanisms

in Chemically Reacting Subsonic and Supersonic Flows

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Massachusetts Institute of Technology

Summary of Progress

The stability of one-dimensional piston-supported detonations has been examined both numerically and analytically. Numerical calculations were conducted for a one-step, first-order, irreversible reaction obeying an Arrhenius rate expression. An approximate linearized stability theory was also developed for the case of high activation-energy reactions and the mechanism of instability identified.

The analysis demonstrates that the interaction between the irreversible temperature fluctuations and the reaction zone induces an oscillatory energy-source field, which then leads to shock perturbations and thereby the temperature fluctuations. The frequencies of all the unstable and stable modes of this system can be predicted. They agree remarkably well with the findings of the numerical calculations and the observations in blunt-body flow experiments.

The problem of direct initiation of gaseous detonations was also examined theoretically, to determine the correlation between the critical

energy and power for successful initiation, and to predict their respective threshold values. The results were found to agree well with the experimental observations of cylindrical detonations in oxy-acetylene mixtures.

One paper is in press and another two papers have been prepared for journal publication.

I. Objective and Scope of the Work

The ultimate objectives of this work are three-fold. First, to determine the mechanism of development of the transverse wave structure in gaseous detonations. Second, to establish a means of estimating the cell size of self-sustained waves. Finally, to determine the necessary requirements for successful direct initiation and the conditions leading to failure. This information is equally important for the understanding of detonations in liquid and solid explosives.

In the first part of this work, we examine the phenomenon of longitudinal oscillations observed in blunt-body flow experiments and in numerical simulations of unsteady one-dimensional detonations. Our main objective is to determine the physical mechanism of instability. In future work, we shall extend the study to the two-dimensional case, to analyze the transverse wave structure of detonation waves.

In the second part of this work, we examine the problem of direct initiation of gaseous detonations, to determine the correlation between the igniter critical energy and average power for successful initiation and to predict their respective threshold values.

The following discussion summarizes the results of these two studies.

II. Results and Discussion

(A) Instability in Gaseous Detonations

Our analysis has demonstrated that the mechanism of instability in gaseous detonations is a non-acoustic one. The sequence of events works out as follows: The pressure waves perturb the shock front and generate irreversible temperature fluctuations. The latter, in turn, are carried by, and interact with the reacting flow, thereby inducing a fluctuating energy-source field. This energy-source field then generates pressure waves which lead to shock perturbations and thereby the temperature fluctuations.

Figure 1 shows the temporal development of the shock pressure for a one-dimensional detonation wave at Chapman-Jouguet conditions. One observes several unstable modes. The first (and lowest-frequency) mode has a period of ~ 20 characteristic chemical times, and a peak-to-peak amplitude of ~ 4 times the steady-state shock pressure p_{ss}. The second mode has a period of ~ 1.5 chemical times and a peak-to-peak amplitude of ~ 0.25 the p_{ss}. The figure also shows higher modes of shorter periods and smaller amplitudes. Preliminary analysis of the two-dimensional case suggests that it is the first mode which produces the transverse wave structure in multi-dimensional detonations.

Figure 2 shows the predictions of the oscillation modes of a typical detonable system for several degrees of overdrive, f. The untagged symbols denote the results of the present theoretical work and the tagged ones denote the results of an exact numerical stability analysis reported in the literature. ω_i and ω_- are the imaginary and

real frequencies of the oscillatory modes. $\omega_i > 0$ denotes an unstable system where the oscillation grows in time. The figure shows that the lowest-frequency modes are the most unstable. Moreover, the present theory is indeed successful in predicting the periods and amplification (or attenuation) rates of all the oscillatory modes.

Figure 3 compares the predictions of oscillation frequencies according to the present theoretical work (solid lines) with the experimental results for blunt-body flows in hydrogen-oxygen systems. Again, the present theory is capable of predicting the periods for both the high- and low-frequency unstable modes.

Work is currently in progress to determine the unstable frequencies for two-dimensional flows and to predict the cell-size in self-sustained waves.

(B) Direct Initiation of Gaseous Detonation

A simple theoretical model was developed to determine the correlation between the igniter's critical energy and power for direct initiation of detonations and to predict their respective threshold values. The model comprises a constant-velocity piston which is set in motion at time $t = 0$. The resulting constant-velocity shock wave heats up the explosive mixture and triggers the chemical reaction. It is shown that for direct initiation, the piston should remain in motion for a time interval, at least, equal to the induction time. The predictions based on this simple model are in good qualitative and quantitative agreement with the experimental findings, reported in the literature on cylindrical

detonations.

Figure 4 shows the calculated shock pressure-time history for different intervals of piston motion $\hat{t}_p$. For $\hat{t}_p < \hat{t}_i$ (where $\hat{t}_i$ is the induction time) the figure shows that the shock decays monotonically to sonic conditions. For $\hat{t}_p > \hat{t}_i$, the shock pressure increases very rapidly and then decays to C-J conditions. For $\hat{t}_p = \hat{t}_i$, the figure shows an initial decay in shock pressure (similar to the case $\hat{t}_p < \hat{t}_i$), followed by two consecutive rapid pressure jumps. Finally, the shock pressure decays asymptotically to the C-J value, p_{C-J}. The figure demonstrates that for successful initiation, the piston should remain in motion for an interval, at least, equal to the induction time.

Figure 5 shows a plot of critical energy E_c versus average igniter power P_{av} for an oxy-acetylene mixture. The solid curve denotes the results predicted by present model, while the symbol (0) denotes experimental results. The figure demonstrates that the present model is indeed successful in predicting both the qualitative and quantitative behavior of the energy-power requirements for direct initiation.

III.   Publications and Reports

See attached Enclosure I.
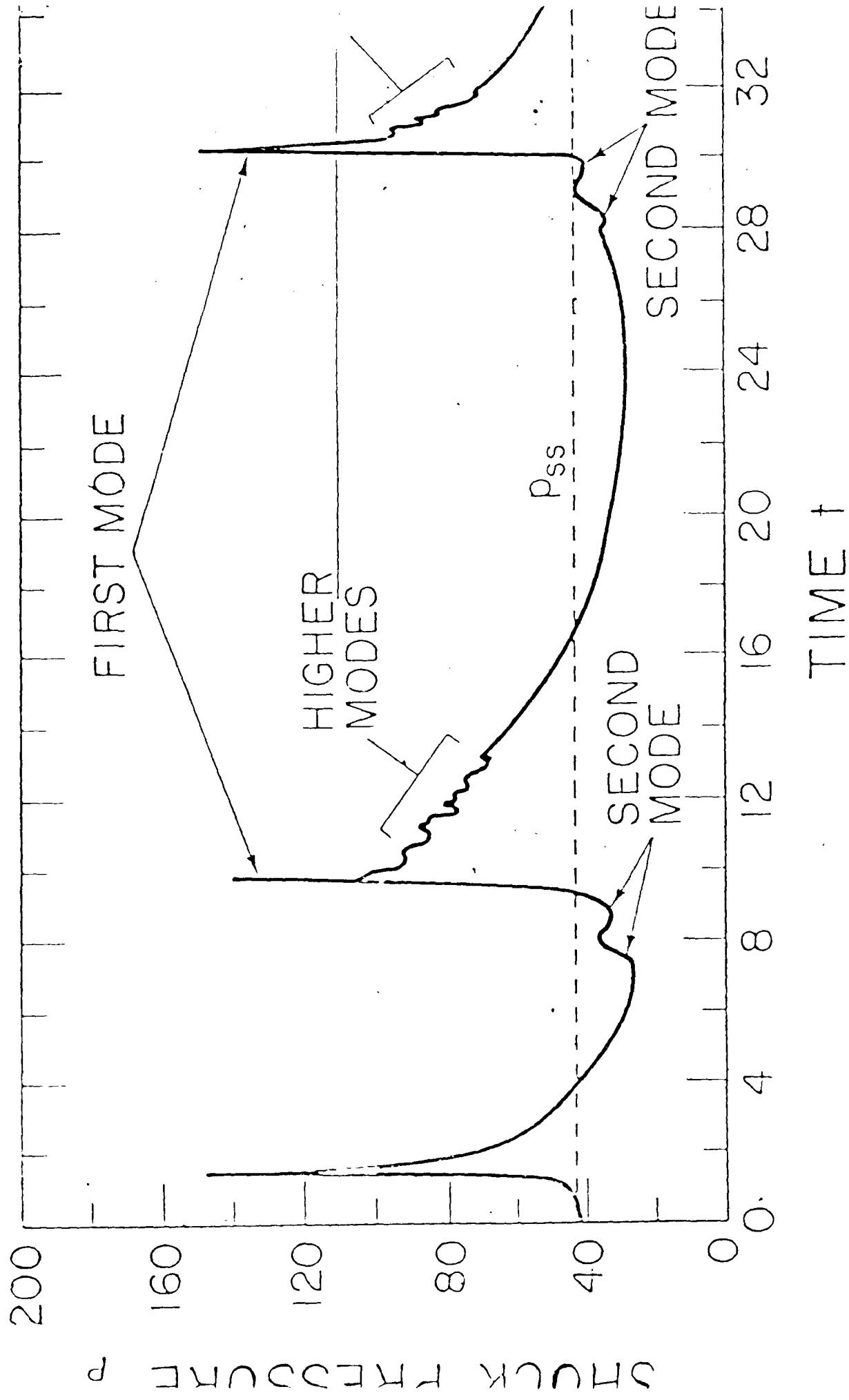

IV.   Professional Personnel

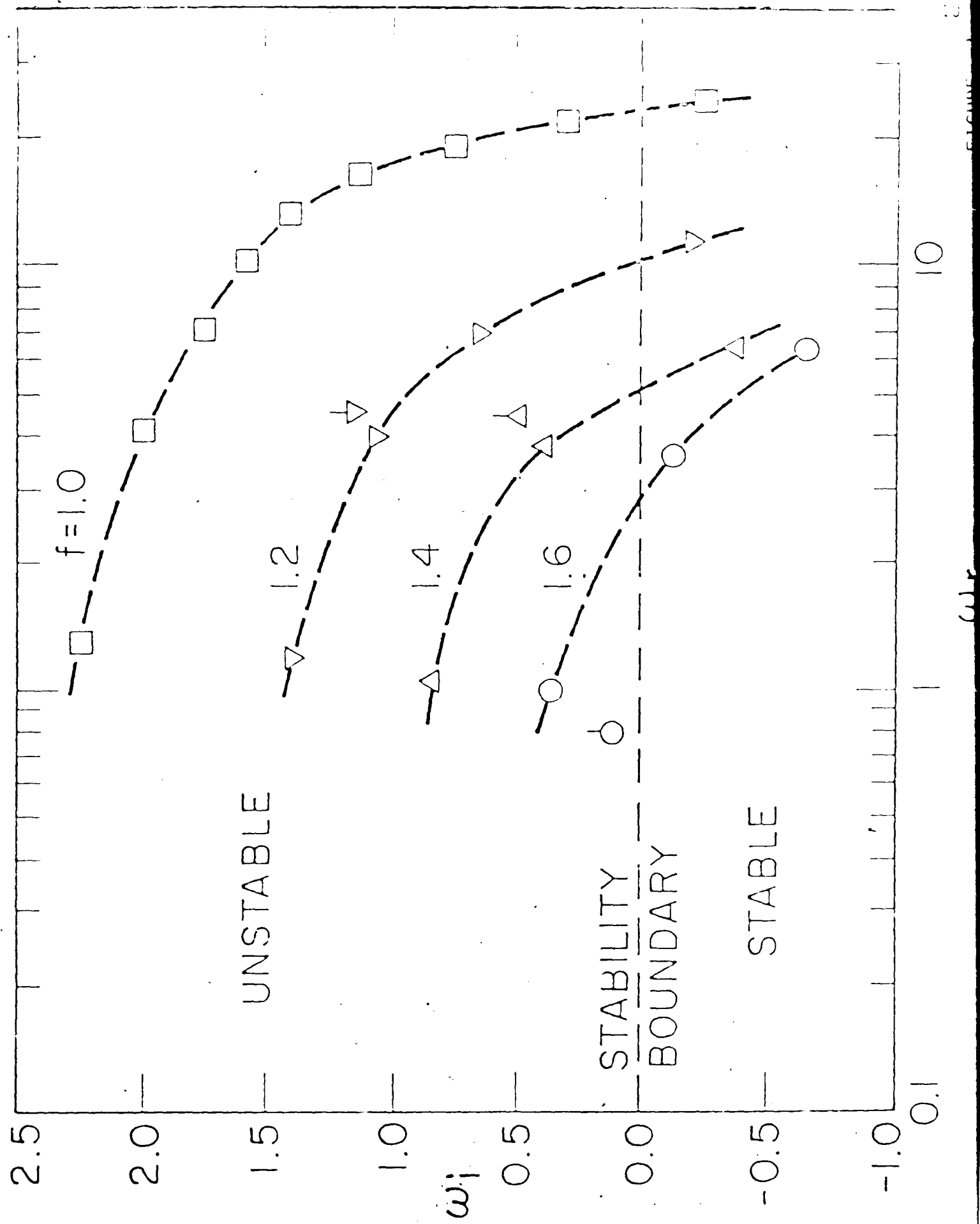Professors T. Y. Toong and G. E. Abouseif

V.   Interactions

Ref. 12 listed in Enclosure I was presented at the 7th International Colloquium on Gasdynamics of Explosions and Reactive Systems, University of Göttingen, Göttingen, Germany, August, 1979.

CAPTION TO FIGURES

Fig. 1   Temporal development of the shock pressure for a one-dimensional

detonation wave at Chapman-Jouguet conditions.

Fig. 2   Predictions of oscillation modes of a typical detonable system

for several degrees of overdrive. Untagged symbols denote the

present theory. Tagged symbols denote exact solutions.

Fig. 3   Predicted oscillation frequencies versus observed frequencies

for hydrogen-oxygen-diluent mixtures. The solid lines indicate

the present theory. Symbols denote experimental results.

Fig. 4   Calculated shock pressure-time history for different intervals

of piston motion.

Fig. 5   Critical energy versus average igniter power for an oxy-acetylene

mixture. The solid curves denotes the present model, (0) denotes
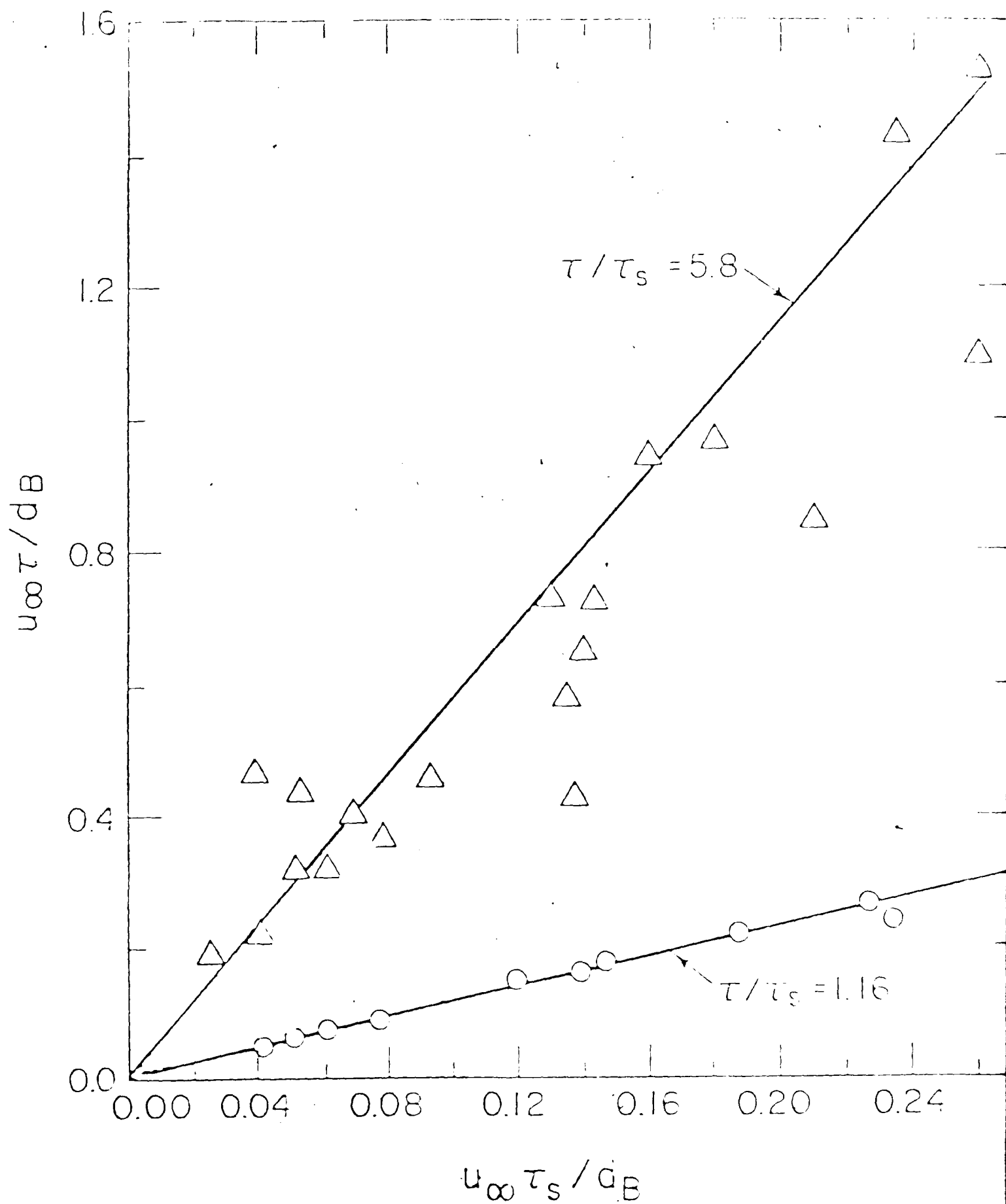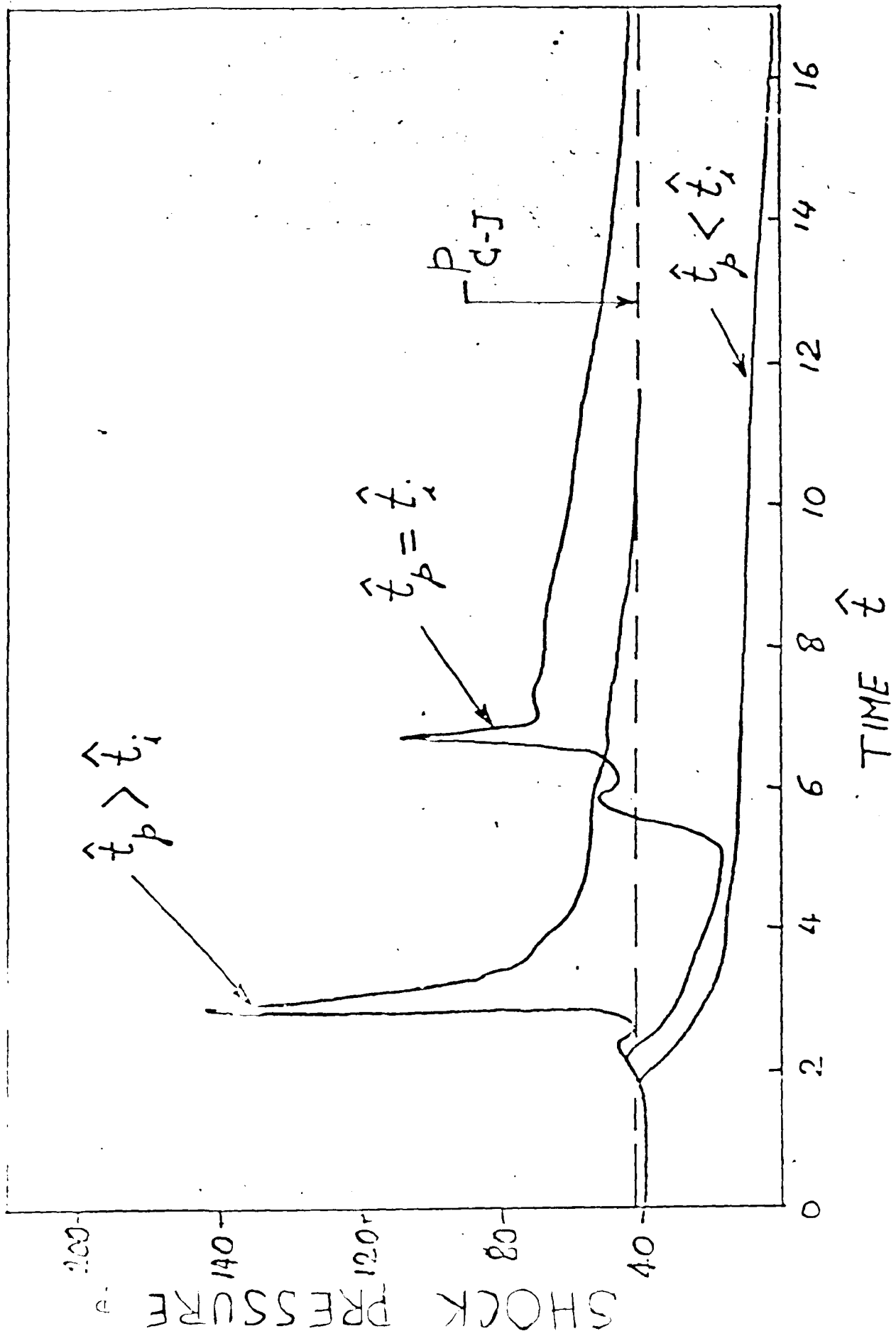
experimental results.

f=1.0

1.2

1.4

1.6

UNSTABLE

STABILITY
BOUNDARY

STABLE

2.5

2.0

1.5

1.0

0.5

0.0

-0.5

-1.0

ω_i

0.1

1

10

ω_r

FIGURE 3

FIGURE

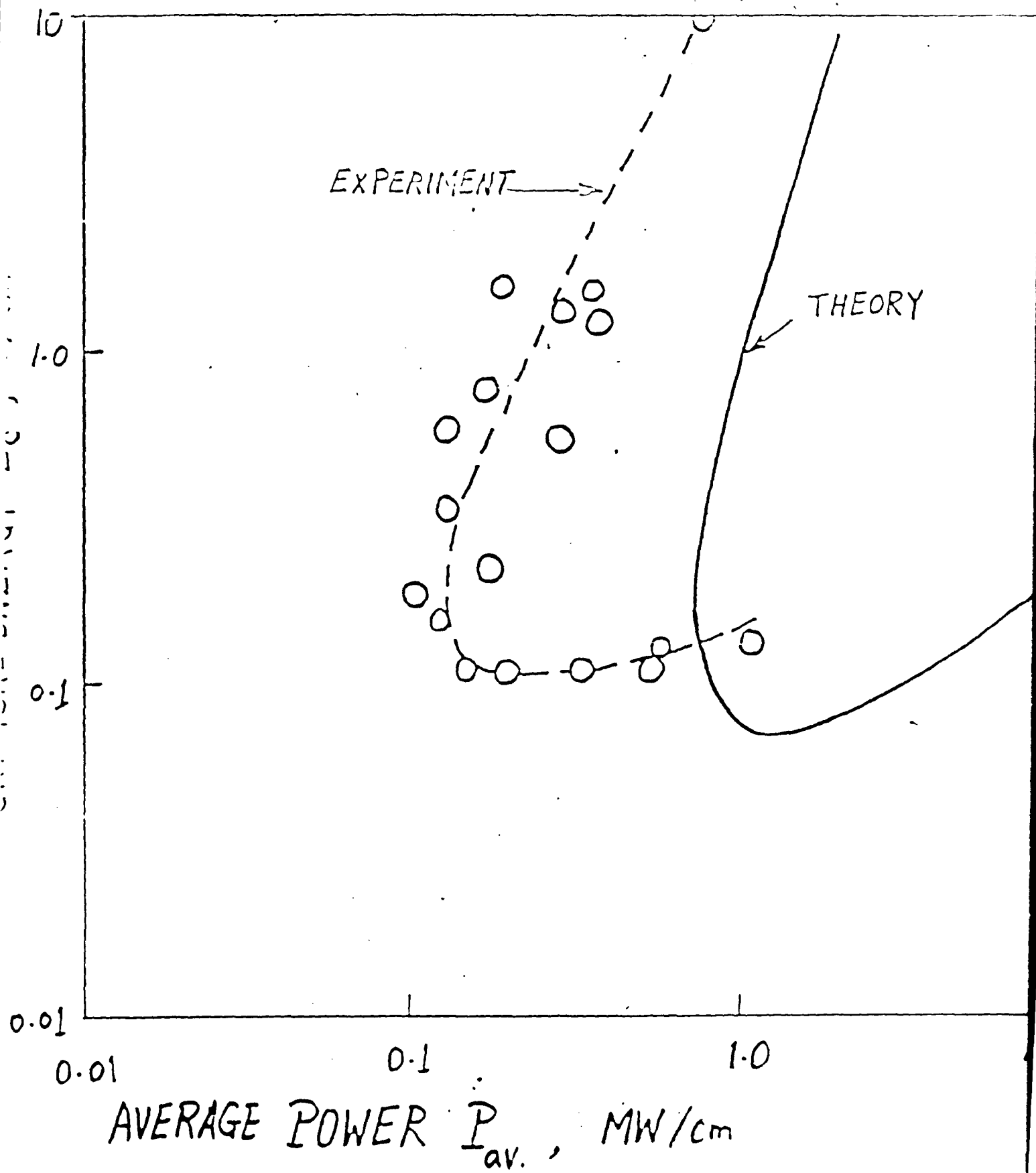AVERAGE POWER $P_{av.}$, MW/cm

FIGURE 5

ENCLOSURE I

Basic Instability Mechanisms

in Chemically Reacting Subsonic and Supersonic Flows

Publications and Reports

(Grants AFOSR-74-2619 and AFOSR-78-3662)

1. Toong, T. Y., "Chemical Effects on Sound Propagation", Combustion and Flame, Vol. 18, pp. 207-216, 1972.

2. Arbeau, P. A., "A Theoretical Study on Generation of Vorticity due to Chemical Reaction", S.M. Thesis, Department of Mechanical Engineering, M.I.T., June 1972.

3. Williams, P. C., "Experiments on Sound Propagating in a Reacting Hydrogen-Chlorine Mixture", Research Report, Combustion and Propulsion Laboratory, Department of Mechanical Engineering, M.I.T., January 1973.

4. Toong, T. Y., "Instabilities in Reacting Flows", invited for presentation at the Fourth International Colloquium on Gasdynamics of Explosions and Reactive Systems, University of California at San Diego, La Jolla, Calif., July 10, 1973; Acta Astronautica, 1, pp. 317-344, 1974.

5. Toong, T. Y., "Basic Instability Mechanisms in Chemically Reacting Subsonic and Supersonic Flows", U.S. Air Force Office of Scientific Research, Final Scientific Report, No. AFOSR-TR-74-0065, November 1973.

6. Toong, T. Y., Arbeau, P., Garris, C. A. and Patureau, J.-P., "Acoustic-Kinetic Interactions in an Irreversibly Reacting Medium", Fifteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pa., pp. 87-100, 1975.

7. Garris, C. A., Toong, T. Y. and Patureau, J.-P., "Chemi-Acoustic Instability Structure in Irreversibly Reacting Systems", presented at the Fifth International Colloquium on Gasdynamics of Explosions and Reactive Systems, University of Orléans, Bourges, France, September 8-10, 1975. Acta Astronautica, 2, pp. 981-997, 1975.

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11. Abouseif, G. E., Toong, T. Y. and Converti, J., "Acoustic- and Shock-Kinetic Interactions in Non-Equilibrium H_2-Cl_2 Reactions", Seventeenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pa., pp. 1341-1351, 1979.

12. Abouseif, G. E. and Toong, T. Y., "Non-Linear Wave-Kinetic Interactions in Non-Equilibrium Exothermic Reactions", Journal of Fluid Mechanics, in press.

13. G. E. Abouseif and T. Y. Toong, "Theory of Unstable One-Dimensional Detonations", submitted for publication in Combustion and Flame, September, 1980.

14. G. E. Abouseif and T. Y. Toong, "On Direct Initiation of Gaseous Detonations", submitted for publication in Combustion and Flame, October, 1980.